

Table of Contents

Foreword	xv
Acknowledgements	xvii
About the Hydraulic Institute and Pump Systems Matter	xxi
Europump	xxi
Executive Summary	xxiii
What is Life Cycle Cost?	xxiv
Getting Started	xxv
Introduction	xxvii

Chapter • One Life Cycle Cost, 1

1.1 General	1
1.2 Elements of Life Cycle Costs	3
1.2.1 Initial Cost (C_{ic})	3
1.2.2 Installation and Commissioning (Start-up) Cost (C_{in})	4
1.2.3 Energy Cost (C_e)	5
1.2.4 Operating Cost (C_o)	6
1.2.5 Maintenance and Repair Cost (C_m)	6
1.2.6 Downtime and Loss of Production Cost (C_s)	8
1.2.7 Environmental Cost, Including Disposal of Parts and Contamination from Pumped Liquid (C_{env})	8
1.2.8 Decommissioning and Disposal Cost, Including Restoration of the Local Environment (C_d)	9
1.3 Calculating Life Cycle Costs	9
1.3.1 General	9
1.3.2 Calculating Present Value (PV)	11
1.3.3 Calculation Chart Using the Simplified Method	13
1.3.4 Example Using the Manual Calculation Chart	13
1.4 Financial Decision Methods - Payback and Internal Rate of Return	17
1.4.1 Simple Payback	17
1.4.2 Discounted Payback	17
1.4.3 Internal Rate of Return	19

Chapter • Two
Pumping System Design, 22

2.1	General	22
2.2	System Design	22
2.2.1	Pipe Size	22
2.2.2	Pump and System Curves	23
2.3	Output Control	25
2.4	Pump Type Selection	25
2.4.1	Pump Types	25
2.4.2	Ways to Reduce LCC When Selecting Pumps	34
2.5	Selecting a Driver	39
2.5.1	Background	39
2.5.2	Types of Electric Motors	42
2.5.3	Efficiency and Energy Costs	44
2.5.4	Variable Frequency Drives	45
2.5.5	Additional Driver and Variable Speed Drive Information	46
2.6	Auxiliary Services	46
2.6.1	Cooling Services	47
2.6.2	Heating	48
2.6.3	Seal Flush Systems	48
2.6.4	Seal Quench Systems	49
2.6.5	Barrier Fluid Systems	49
2.6.6	Lubrication Systems for Sleeve Bearings	49
2.7	Power Transmission	49
2.7.1	Summary of Power Transmission Characteristics	49
2.8	System Effectiveness in Design and Output Control: A New Concept	50
2.8.1	Process Requirements	50
2.8.2	Specific Energy	54
2.8.3	Summary	60
2.9	Monitoring and Sustaining the System	61
2.9.1	Maintaining Pump Efficiency	61
2.9.2	Organizing Maintenance and Monitoring	67

Chapter • Three
Methods for Analyzing Existing Pumping Systems, 70

3.1	Introduction	70
3.2	Improving the System	70
3.3	System Components	71

3.3.1 Pump	71
3.3.2 Control or Throttle Valves	72
3.3.3 Components	72
3.4 System Loads	73
3.5 Determining the Rates of Flow	73
3.6 Example of Minimizing Losses by Balancing a Branched System	74
3.6.1 Balancing the System	74
3.6.2 Changing the Pump	76
3.7 Examples for Achieving Energy Savings in Existing Systems	78
3.7.1 Example 1: Waste Collection System With Oversized Pumps	78
3.7.2 Example 2: System With a Problem Control Valve	82

Chapter • Four

Examples of LCC Analysis, 86

4.1 Waste Collection System Example	86
4.1.1 Conclusion	87
4.2 Problem Control Valve Example	89
4.2.1 Conclusion	90

Chapter • Five

Effective Procurement Using LCC, 94

5.1 Introduction	94
5.2 Enquiry Documentation	94
5.3 Life Cycle Cost (LCC)	95
5.4 Work Methodology	95
5.5 Contract Boundaries	96
5.6 Evaluating Tenders	96
5.7 Inspection - Performance Bonus or Penalty	96
5.8 Example	96

Chapter • Six

Recommendations for Designing and Procuring Pumping Systems, 98

Chapter • Seven

References, 102

Chapter • Eight

Glossary of Terms and Symbols, 105

Appendix A

System Curves, 107

A.1 System Curves	107
A.1.1 Operating Duty Point	107
A.1.2 Characteristic Curves	109
A.1.3 Branched Piping Systems	120
A.1.4 Duty Modifications	124
A.1.5 Viscous and Non-Newtonian Liquids	127
A.2 Computer Software	128

Appendix B

Pumping Output and System Control, 129

B.1 Output Control	129
B.1.1 General	129
B.1.2 Determining Flow Requirements	130
B.2 System Control	133
B.2.1 Control Parameters	134
B.2.2 Start–Stop Control	136
B.2.3 Throttling Control	139
B.2.4 Variable Speed Regulation	140
B.2.5 Eccentric Radius Adjustment in Vane Cell Pumps	143
B.2.6 Stroke and Speed Regulation of Reciprocating Positive Displacement Pumps	143
B.3 Summary	144

Appendix C

Pump Efficiencies, 146

C.1 Pump Efficiencies	146
C.1.1 General	146
C.1.2 Nomenclature	149
C.2 Regulation of the European Commission (EU) No 547/2012 for Water Pumps	150

C.2.1 Overview	150
C.3 U.S. DOE Conservation Standard for Certain Clean Water Pumps	150
C.3.1 Overview	150

Appendix D

Case Histories–Cost Savings Examples, 152

D.1 Introduction	152
Case History 1: Building services.....	155
Case History 2: Pulp and paper manufacture.	157
Case History 3: Chemical processing.	159
Case History 4: Water supply.....	161
Case History 5: Waste water.	163
Case History 6: Steel making.....	165
Case History 7: Petrochemical processing.	167
Case History 8: Domestic electrical appliance.....	169
Case History 9: Mining.....	171
Case History 10: Power plant.....	173
Case History 11: Building services.....	175
Case History 12: Building services.....	176
Case History 13: Chemical industry.....	178
Case History 14: Food industry.	180

Appendix E

Drivers, Transmissions, and Variable Speed Drives, 182

E.1 Induction Motors	182
E.1.1 Introduction	182
E.1.2 Definitions of Motor Efficiency	183
E.1.3 Minimum Efficiency	185
E.1.4 Selecting a Motor.....	191
E.2 Considerations for Electric Motors to Improve System Efficiency.....	192
E.2.1 Motor Management Best Practices for Energy Efficiency.....	193
E.3 Variable Frequency Drives (VFD).....	196
E.3.1 Overview of VFDs	196
E.4 Power Transmission	206
E.4.1 Efficiency and Characteristics of Various Types of Transmissions	206
E.5 Key takeaways	212

List of Figures

Typical LCC for a medium-sized industrial pumping system	xxvi
1.1 Manual calculation chart of LCC.	15
1.2 Example 4.1.b using the manual calculation chart	16
2.1 Key cost components for a pumping installation as related to pipe size	23
2.2 Typical pump performance and system curves – rotodynamic pumps.	24
2.3 Typical pump performance and system curves – positive displacement pumps.	24
2.4 Pump selection diagram for rotodynamic pumps with standard drivers handling clean liquids.	28
2.5 Average attainable industrial pump efficiency, η_{avg} , for rotodynamic volute pumps with closed impellers and for clean cold water	29
2.6 Typical pump selection diagram for positive displacement pumps (PD pumps).	30
2.7a Maximum attainable efficiencies for PD pumps with fluids below 100 mPa s.	31
2.7b Maximum attainable efficiencies for PD pumps with fluids below 1000 mPa s.	32
2.8 Indication of the influence of viscosity on the efficiency for different types of PD pumps	33
2.9 Example of a performance curve for a rotodynamic centrifugal (radial flow) pump showing the preferred operating region 35	
2.10 Variations in efficiency for a 30-kW 4-pole motor	44
2.11 Efficiency curve of a typical variable frequency drive	46
2.12 Duration diagrams for two different pumping systems	51
2.13 System curve	52
2.14 Lines of constant efficiency (broken) superimposed over speed-regulated pump curves (solid).	53
2.15 The operating point on the reduced speed curve moves relatively higher on the pump curve as the speed is reduced. . . .	53
2.16 Example of specific energy as a function of static head and overall efficiency	56

2.17	Three different system curves A, B and C, all passing through the same duty point at full speed and the associated curves for specific energy	58
2.18	Throttling a valve changes the rate of flow by adding pressure drop in the valve, thus moving the duty point along the pump curve	59
2.19	Compared with regulation by throttling, variable speed drives always save on energy	59
2.20	Parallel pump operation	60
2.21	Reduced efficiency and head caused by leakage losses	61
2.22	Clearances* from left to right: semi-open impeller clearance; closed impeller radial clearance	62
2.23	Examples of clearances (s) in rotating positive displacement pumps: a) screw pump; b) gear pump	65
2.24	Pressure signals of a hydraulically acting diaphragm pump: a) healthy pressure signal; b) leakage in the hydraulic chamber (replenishing window [RW])	66
2.25	Structure-borne noise signal and pressure signal of a reciprocating PD pump: a) healthy pump; b) leaking suction valve	67
2.26	Preventive maintenance in terms of total maintenance costs	68
3.1	Branched piping system showing the rate of flow in the various paths	74
3.2	Branched system showing the differential pressure in bar across the throttle valves needed to throttle the rate of flow to the set value	75
3.3	The branched piping system with flows balanced and pump impeller trimmed to eliminate excessive differential pressure across the control valves	76
3.4	The pump curve for the larger and smaller impeller trim; rate of flow for unbalanced flow is 166 m ³ /h (720 USgpm), balanced rate of flow 120 m ³ /h (520 USgpm)	77
3.5	Pressurized forced main system pumping down the sump using on/off control; evaluating changing pumping rate for lower operating costs	78
3.6	Total head as a function of rate of flow for the sump pump system	80
3.7	Pump curve for the pump selected for 30 m ³ /h	81
3.8	Sketch of pumping system in which the control valve fails	83

3.9	System resistance curve and pump curve showing the operation of the system	84
3.10	Pump curves and system curves showing the operation of the original system and the modified pump impeller.	84
4.1	LCC comparison for the waste collection system	88
4.2	LCC comparison for the problem control valve system	91
4.3	LCC comparison for the problem control valve system	93
6.1	New pumping system	99
6.2	Existing pump systems.	100
A.1a	Operating duty point at $H_{\text{pump}} = H_{\text{syst}}$ for a rotodynamic pump	108
A.1b	Operating duty point at $H_{\text{pump}} = H_{\text{syst}}$ for a positive displacement pump	108
A.2	Example of simple piping system	109
A.3	System curve	111
A.4	Piping systems with the same static head	111
A.5	Piping system with $H_{\text{stat}} \approx 0$; $H_{\text{syst}} = H_j$	112
A.6	System with $H_j \approx 0$	112
A.7	Resultant pump curve for series operation.	113
A.8	Parallel pump operation	113
A.9	Parallel operation of two similar pumps with different system curves.	114
A.10	Pumping systems with different static heads	115
A.11	System curve with varying static head	116
A.12	Consequences of incorrectly calculated pipe losses	117
A.13	The effect of deposits (scale, rust, etc.) on pipelines	118
A.14	The effect of varying levels.	119
A.15	The effect of adding margins to calculated system curve.	119
A.16	Branched circulation system.	121
A.17	Branched piping system, $H_{\text{stat}} = 0$	121
A.18	Branched pipe system with different static head	122
A.19	Branched piping system with positive suction static head	123
A.20	Pump performance by reduced impeller diameter	124
A.21	Pump performance by variable speed	125
A.22	Variable pitch propeller pumps	126

A.23	Mixed-flow pumps with adjustable inlet guide vanes	126
A.24	Pump and system curves for more viscous liquids as compared with water	127
A.25	Pump and system curves for water and pulp suspension	128
B.1	The duty point is the intersection between the pump and system curves: rotodynamic pump (RD); positive displacement pump (PD)	130
B.2	Flow as a function of time – operating curve	131
B.3	Duration curve of the flow	131
B.4	Graphical integration method to determine mean rates of flow	132
B.5	Illustration of Equations B-1 and B-2	133
B.6	Control at (a) constant pressure, (b) constant flow, and (c) proportional level control	137
B.7	Pump and drive system	140
B.8a	Examples of performance curves for a speed regulated rotodynamic pump	142
B.8b	Performance curves for PD-pumps with speed regulation.	142
B.9	Pump power requirement for speed-regulated rotodynamic pump with hydraulic coupling transmission	143
B.10	Typical stroke adjustable drive element of a reciprocating positive displacement pump	144
B.11	Power requirement for single stage rotodynamic pumps with flow control using various methods, in a system with a low ratio: H_{stat}/H_0	145
C.1	Typical single-stage, single-suction volute casing pump	147
C.2	Maximum attainable efficiencies, η_{max} , of single-stage, single-suction volute casing pumps dependent on specific speeds and rates of flow	148
C.3	Average attainable industrial pump efficiencies, η_{avg} , of single-stage, single-suction volute casing pumps dependent on specific speeds and rates of flow	149
E.1	Major features of an electric motor that affects efficiency	184
E.2	Motor efficiency versus load EPAct and NEMA premium comparison	191
E.3	Life cycle cost of an industrial AC induction motor	193
E.4	75 kW (100 hp) motor efficiency and power factor as a function of load	195

E.5	VFD block diagram	197
E.6	VFD operator interface (OI)/user interface (UI)	197
E.7	VFD with optional bypass	199
E.8	Pump system components	200
E.9	Constant torque and variable torque pump load as a function of frequency or speed	201
E.10	A constant torque V/Hz ratio supplied to the motor	202
E.11	A variable torque V/Hz ratio supplied to the motor	202

List of Tables

1.1	Factor C_p/C_n for a single cost element after n years	12
1.2	Discount factor (df) for constant yearly expenditures	14
1.3	Simple Payback	17
1.4	Discounted payback (Net Present Value)	18
1.5	Internal Rate of Return by trial and error	20
1.6	Internal Rate of Return by Excel Function	20
2.1	Control methods – applications and limitations	26
2.2	Application ranges of positive displacement pumps	38
2.3	Properties of commercially available PD pumps; PH/PS = hydraulic power /shaft power	40
2.4	Positive and negative aspects of specific transmissions	50
3.1	Operation and annual operating cost of the three-branched piping system in the various operating modes	77
3.2	Work sheets (a) and (b) showing how the rate of flow is calculated by pumping down and filling a sump	79
3.3	Cost comparison for energy cost for the 60 m ³ /h (260 USgpm) and 30 m ³ /h (130 USgpm) pumps	82
3.4	Cost comparison for Options A through D in the system with a failing control valve	85
B.1	Control methods – applications and limitations	134
B.2	Some control parameters used for pumps	136
D.1	Summary of Case Histories	153
E.1	IEC 60034-30 compared to NEMA MG-1	191
E.2	Motor energy cost comparison	193